# LHC/ILC complementarity for Higgs in extra dimensions

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ILC Physics in Florence

- **Higgs phenomenology in ADD model**
- **Higgs and radion phenomenology in RS model**
- **Conclusions**

**Based on**
M. Battaglia, DD, J. Gunion, in preparation
M. Battaglia, DD, J. Gunion, J. Wells, LCWS 2005 and hep-ph/0402062
DD, B. Grzadkowski, J. Gunion, M. Toharia, Nucl.Phys.B671:243 2003
M. Battaglia, S. De Curtis, A. De Roeck, DD, J. Gunion, Phys.Lett.B568:92 2003

# Recent motivation for extra dimensions: the hierarchy problem, or why

$$M_W << M_{Pl}$$

**New idea: geometry may be responsible for the hierarchy**

- Large volume of $\delta$ extra dimensions (Arkani-Hamed, Dimopoulos, Dvali, Antoniadis)

$$\overline{M}_{Pl} = \overline{M}_D^{1+\delta/2} V^{\delta/2}$$

$\overline{M}_D \sim TeV$ fundamental Planck scale, $V_\delta$ compactification volume

- Strong curvature of the extra dimension (Randall, Sundrum)

$$\overline{M}_{Pl} = \Lambda \exp\left(\pi k R\right)$$

$\Lambda \sim$ TeV, $kR \sim$ 11-12

Both can modify the Higgs phenomenology.

# Higgs phenomenology in ADD model

(Arkani-Hamed, Dimopoulos, Dvali, Antoniadis)

Gravity in $D = 4 + \delta$ dimensions, SM particles localized on a 3 dimensional brane.

$$S = \frac{\overline{M}_D^{\,2+\delta}}{2} \int d^D x \sqrt{|g|} R + \int d^4 x \sqrt{-g_{\mathrm{ind}}} \mathcal{L}_{\mathrm{SM}}$$

$$g_{AB} = \eta_{AB} + \frac{2}{\overline{M}_D^{\,1+\delta/2}} h_{AB}, \quad h_{AB} = \sum_{\vec{n}} \frac{1}{\sqrt{V_\delta}} h_{AB}^{(\vec{n})}(x) e^{-i \sum_{j=1}^{\delta} n_j y_j}$$

Light KK states (KK gravitons and graviscalars)

$$m_{\vec{n}} = \frac{|\vec{n}|}{R} \qquad \Delta m_{\vec{n}} \sim 10^{-3}\mathrm{eV} - 10\,\mathrm{MeV}, \;\; \delta = 2 - 6$$

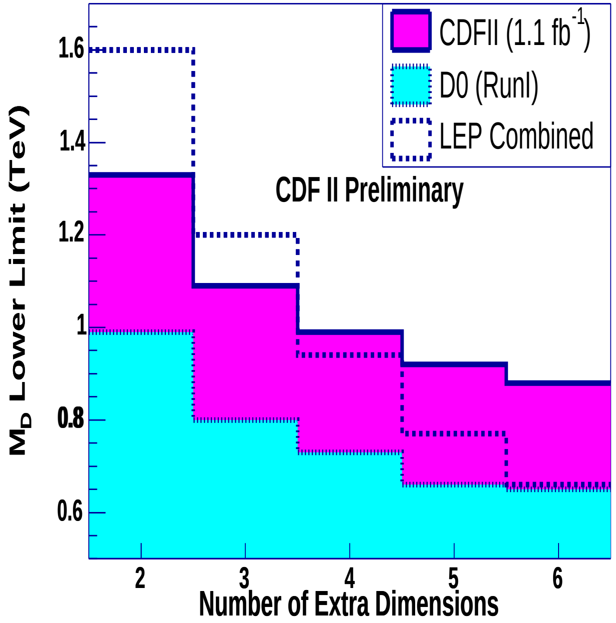
and very long lived ($\sim 10^{10}$yr).
Interactions with SM fields

$$-\frac{1}{\overline{M}_{Pl}} G^{(\vec{n})\mu\nu} T_{\mu\nu} + \frac{1}{\overline{M}_{Pl}} \sqrt{\frac{\delta - 1}{3(\delta + 2)}} H^{(\vec{n})} T_\mu^{\ \mu}$$

## 95% CL Limits on $M_D$ (TeV) from colliders

**Generic signature: a final state with missing $\not{E}_T$, due to the KK excitations which are radiated away into the extra dimensions.**

**Collider bounds: from graviton emission process at LEP2 ($e^+e^- \to \gamma \not{E}_T$, $e^+e^- \to Z \not{E}_T$ ) and Tevatron ($p\bar{p} \to \gamma \not{E}_T$ ,$p\bar{p} \to jets\, \not{E}_T$ ).**



$$M_D = (2\pi)^{\frac{\delta}{\delta+2}} \overline{M}_D$$

**The presence of an interaction between the Higgs $H$ and the Ricci scalar curvature of the induced 4-dimensional metric $g_{ind}$,**

$$S_\xi = -\xi \int d^4x \sqrt{g_{ind}} R(g_{ind}) H^\dagger H$$

**generates, after the shift $H = (\frac{v+h}{\sqrt{2}}, 0)$, a mixing term** (Giudice, Rattazzi and Wells) **$(H^{(\vec{n})} = \frac{1}{\sqrt{2}}(s_{\vec{n}} + i a_{\vec{n}}))$**

$$\mathcal{L}_{mix} = \epsilon h \sum_{\vec{n}>0} s_{\vec{n}} \qquad (1)$$

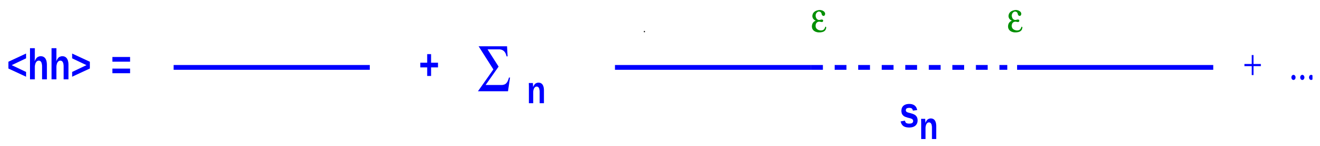
**with**

$$\epsilon = -\frac{2\sqrt{2}}{\overline{M}_{Pl}} \xi v m_h^2 \sqrt{\frac{3(\delta-1)}{\delta+2}} \, .$$

**$\xi$ is a dimensionless parameter and $s_{\vec{n}}$ is a graviscalar KK excitation.**

# Invisible Higgs width

This mixing generates an oscillation of the Higgs itself into the closest KK graviscalar levels which are invisible. The mixing invisible width $\Gamma_{inv}$ calculated by extracting the imaginary part of the mixing contribution to the Higgs self energy (Giudice et al, Wells):



In an equivalent way: first the mixing term can be eliminated with the transformation to the new fields $h'$ and $s'_{\vec{n}}$ and in computing a process such as $WW \longrightarrow h' + \sum_{\vec{m}>0} s'_{\vec{m}} \longrightarrow F$, consider the full coherent sum:

$$\mathcal{A}(WW \to F)(p^2) \sim \frac{g_{WWh} g_{hF}}{p^2 - m_h^2 + i m_h \Gamma_h + i G(p^2) + F(p^2) + i\bar{\epsilon}}$$

**Writing** $F(p^2) = F(m_{h_{eff}}^2) + (p^2 - m_{h_{eff}}^2)F'(m_{h_{eff}}^2) + \ldots$,
**where** $m_{h_{eff}}^2 - m_h^2 + F(m_{h_{eff}}^2) = 0$,

$$\mathcal{A}(WW \to F)(p^2) \sim \frac{g_{WWh}\,g_{hF}}{(p^2 - m_{h_{eff}}^2)[1 + F'(m_{h_{eff}}^2)] + i m_{h_{eff}}(\Gamma_h + \Gamma_{inv})}$$

**with**

$$m_{h_{eff}}\Gamma_{inv} = G(p^2)|_{m_{h_{eff}}^2} = -\epsilon^2 \mathrm{Im}\left[\sum_{\vec{m}>0} \frac{1}{p^2 - m_{\vec{m}}^2 + i\bar{\epsilon}}\right]_{m_{h_{eff}}^2}$$

**In conclusion:**

$$\sigma(WW \to h' + \sum_{\vec{n}>0} s_{\vec{n}} \to F) = \sigma_{SM}(WW \to h \to F) \left[\frac{1}{1 + F'(m_{eff}^2)}\right]^2 \times \left[\frac{\Gamma_{h\to F}^{SM}}{\Gamma_h^{SM} + \Gamma_{inv}}\right]$$

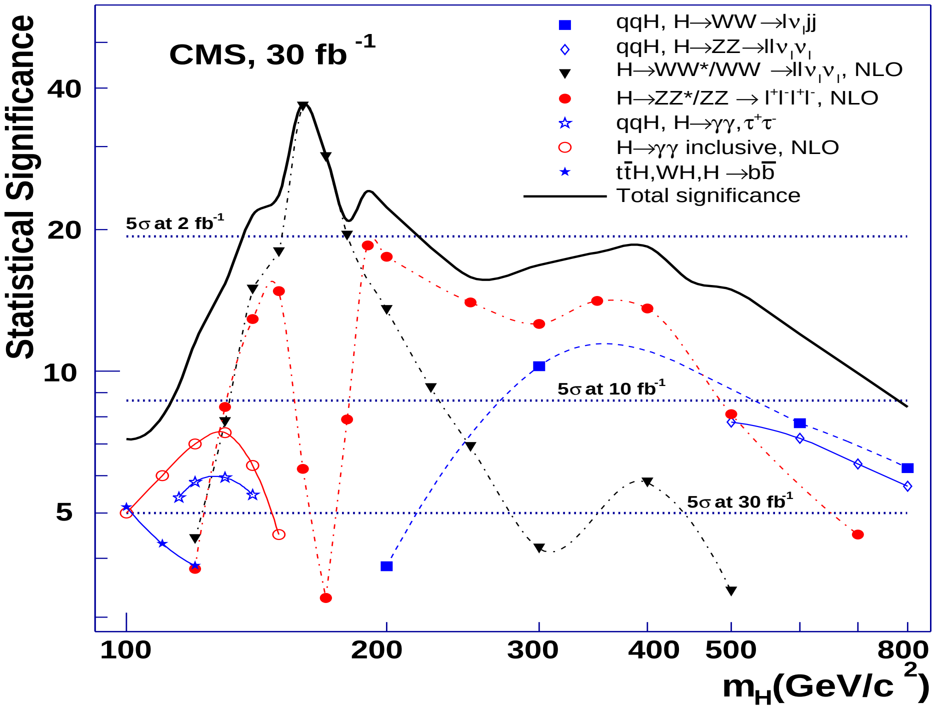
$$
\begin{aligned}
G({m_h}^2) \quad & \rightarrow -\frac{\epsilon^2}{2} Im \int dm^2 \rho_\delta(m) \frac{1}{{m_h}^2 - m^2 + i\bar{\epsilon}} \\
&= -\epsilon^2 \frac{1}{4} \frac{\overline{M}_{Pl}^2}{M_D^{2+\delta}} S_{\delta-1}(-\pi)({m_h}^2)^{(\delta-2)/2}
\end{aligned}
$$

$$
\begin{aligned}
\Gamma_{inv} \quad \sim \quad & (16\, MeV) 20^{2-\delta} \xi^2 S_{\delta-1} \frac{3(\delta-1)}{\delta+2} \\
& \times \left( \frac{m_h}{150\, GeV} \right)^{1+\delta} \left( \frac{3\, TeV}{M_D} \right)^{2+\delta}
\end{aligned}
$$

**$S_\delta = 2\pi^{\delta/2}/\Gamma(\delta/2)$ denotes the surface of a unit radius sphere in $\delta$ dimensions.**

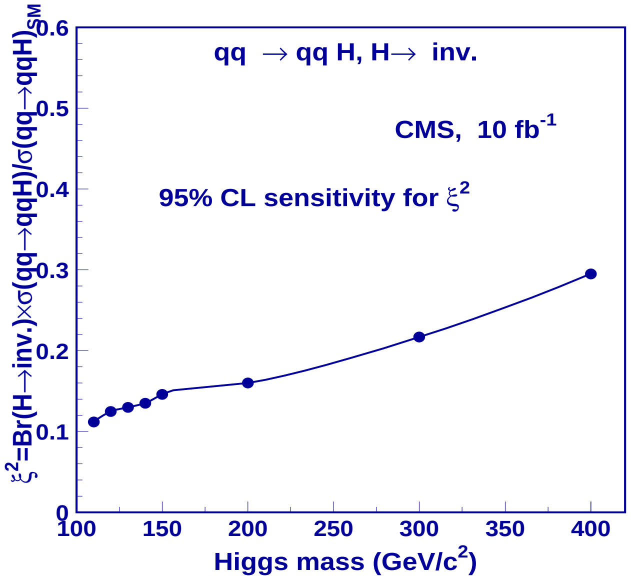
- **For a light Higgs both the wave function renormalization and the mass renormalization effects are small: $F'(m^2_{h\,eff}) \sim \xi^2 \frac{m_h^4}{\Lambda^4}$, where $\Lambda \sim M_D$, therefore quite small for the $m_h \ll M_D$.**
- **For a light Higgs the invisible width causes a significant suppression of the LHC rates in the standard visible channels**

- In the following analysis: for visible channels we have used the CMS statistical significance



- **For invisible Higgs** (Fusion channel: Eboli and Zeppenfeld, Di Girolamo et al, Abdullin et al, CMS note)

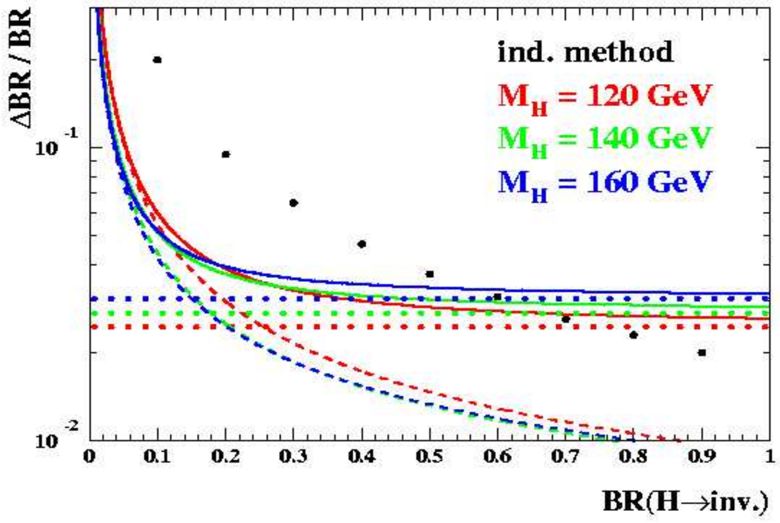
**Higgs boson production in $qq \rightarrow qqVV \rightarrow qqh \rightarrow qq\ inv$. Signal characterized by two very energetic forward jets well separated in pseudorapidity. With 100 fb$^{-1}$ sensitive at 5$\sigma$ at $B_{inv} \sim 0.1$.**



**$ZH$ channel (Dilepton +missing $\not\!\!E_T$ )** (Godbole, Guchait, Mazumdar, Moretti and Roy, Davoudiasl, Han and Logan) **: $B_{inv} \sim 0.42(0.70)$ probed at 5$\sigma$ level for $m_H = 120(160)$ GeV with 100 fb$^{-1}$.**

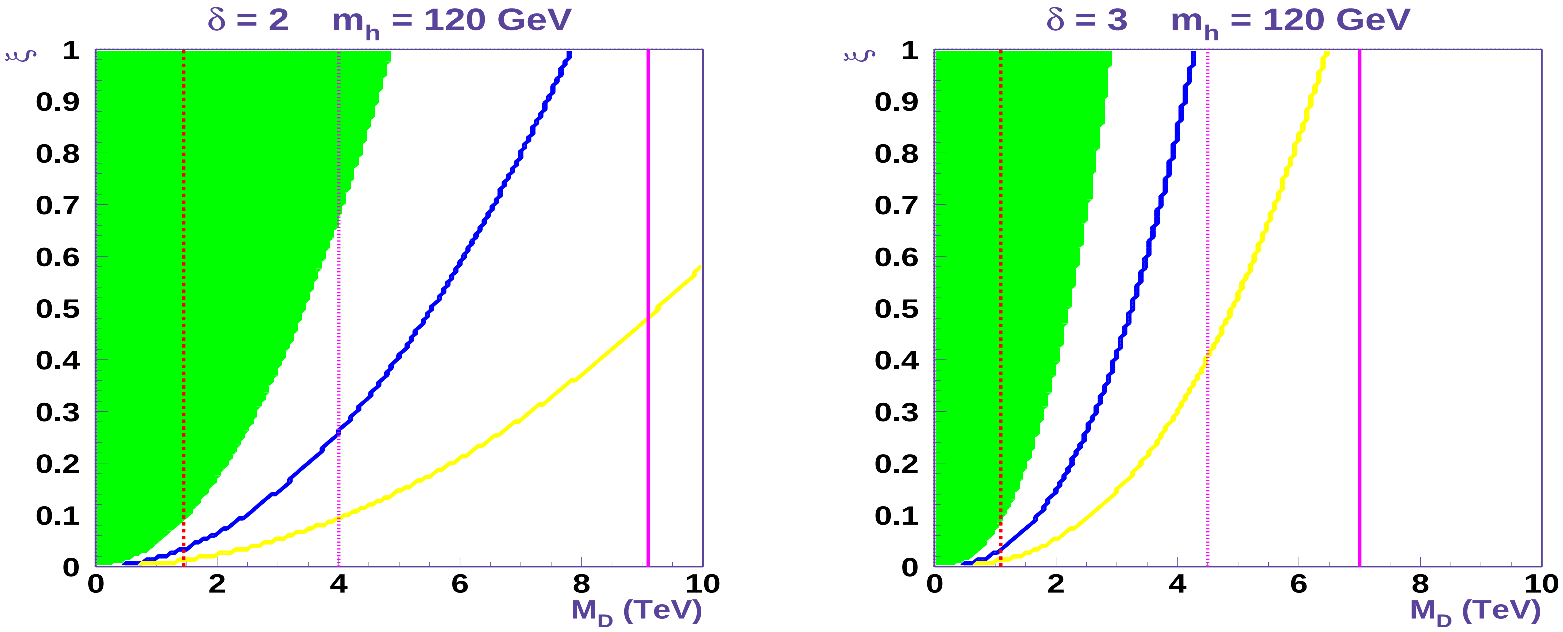
# Sensitivity to $\Gamma_{inv}$ at the ILC

**Signal process: $e^+e^- \to ZH \to$ two jets+$\not{E}_T$. Relative accuracy of the measurement of the invisible branching as a function of the branching ratio, for $m_H = 120,\ 140,\ 160$ GeV at $\sqrt{s}$ =350 GeV for 500 fb$^{-1}$ (Schumacher).**

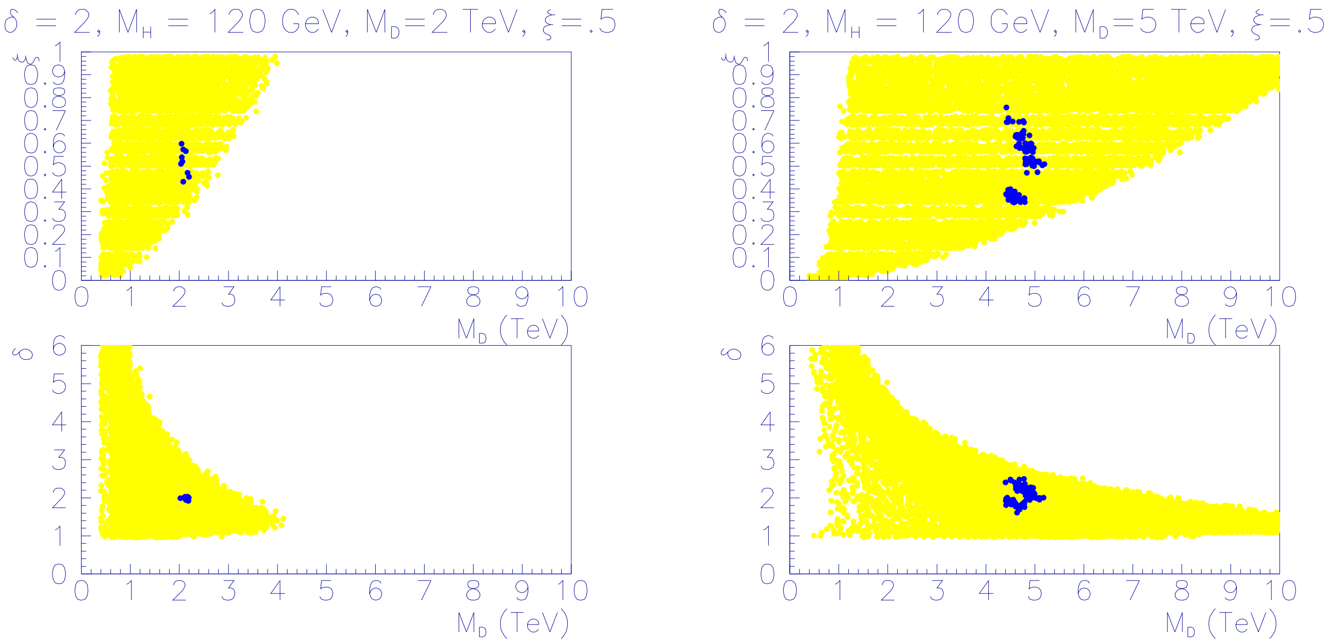


**Invisible Higgs discovered down to $B \sim 0.02$.
Recent proposal: working at $\sqrt{s} = 230$ GeV for L=50 fb$^{-1}$ (Richard, Bambade).**

The green regions: the Higgs signal at the LHC $< 5\ \sigma$ for 100 $fb^{-1}$. The regions above the blue line are where the LHC invisible Higgs signal in the $WW$-fusion channel $> 5\ \sigma$. The purple line shows the upper limit on $M_D$ which can be probed at the $5\ \sigma$ by the analysis of jets/$\gamma$ with missing energy at the LHC. The red dashed line 95% CL lower limit from Tevatron and LEP/LEP2 limits. The regions above the yellow line are the parts where the ILC invisible Higgs signal $> 5\ \sigma$ assuming $\sqrt{s} = 350$ GeV and $L = 500$ fb$^{-1}$.



# Determining ADD parameters from LHC and ILC data

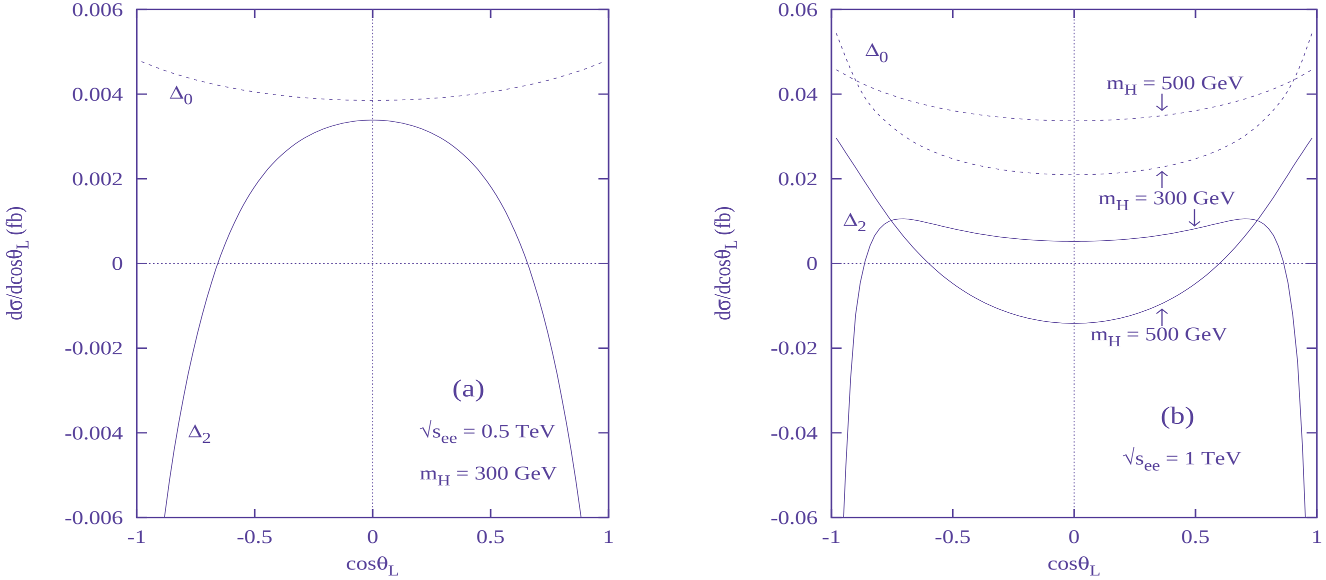


**The yellow regions are the 95% CL regions using only $\Delta\chi^2(LHC)$. Blue regions or points are the 95% CL regions using $\Delta\chi^2(LHC+ILC)$.**
**LHC: visible and invisible Higgs signal assuming SM production rate for 100 $fb^{-1}$.**
**ILC visible ($WW^*$, $b\bar{b}$) and the invisible branching ratio at $\sqrt{s} = 350$ GeV.**
**ILC $\gamma + \not{E}_T$ signal at two different energies: at $\sqrt{s} = 500$ GeV and $\sqrt{s} = 1000$ GeV of respectively, 1000 fb$^{-1}$ and 2000 fb$^{-1}$, respectively, $P_{e^-} = 0.80$, $P_{e^+} = 0.60$, $E_\gamma < 0.625\ E_{beam}$. Polarization extremely effective in reducing $e^+e^- \rightarrow \gamma\nu\bar{\nu}$ background.**

# KK graviton and graviscalar interference with Higgs

(Datta, Gabrielli, Mele)

**Virtual KK graviton, $\Delta_2$, and graviscalar, $\Delta_0$, interference with resonant Higgs, present also when $\xi = 0$. $e^+e^-(WW) \rightarrow \nu\bar{\nu}P\bar{P}$ , $P = W, Z, t$ Relevant only for heavy Higgs, low $M_D$ and $\delta = 2$. $\Delta_0 \sim 2\%$ for $m_H = 800$ GeV.**



**The KK graviscalar (dashed), and the KK graviton contribution (continuous) to the total interference with the SM amplitude in the angular distribution at $\sqrt{s} = 500$ and 1000 GeV. Largest effect in $t\bar{t}$. With suitable cuts grav/SM $O(\%)$ for $m_H = 800$ GeV.**

# Higgs and radion phenomenology in RS model

Usual 2-brane RS 5D warped space scenario

$$ds^2 = e^{-2\sigma(y)}\eta_{\mu\nu}dx^\mu dx^\nu - b_0^2 dy^2$$

where $\sigma(y) = kb_0|y|$. Gravitational fluctuations around the above background metric:

$$\eta_{\mu\nu} \longrightarrow \eta_{\mu\nu} + \epsilon h_{\mu\nu}(x,y) \qquad b_0 \longrightarrow b_0 + b(x)\,.$$

The canonically normalized radion field $\phi_0(x)$ is defined by:

$$\phi_0(x) = \Lambda_\phi e^{-kb(x)/2}$$

with $\Lambda_\phi = \sqrt{6}\,\overline{M}_{Pl}\Omega_0$, $\Omega_0 \equiv e^{-kb_0/2}$ is the warp factor.
A mixing among the radion and the Higgs $\widehat{H}$ is induced by (Giudice, Rattazzi, Wells)

$$S_\xi = \xi \int d^4x\sqrt{-g_{\text{vis}}}R(g_{\text{vis}})\widehat{H}^\dagger\widehat{H}\,,$$

# KK graviton excitations

## KK mode expansion in the extra dimension

$$h_{\mu\nu}(x,y) = \sum_n h^n_{\mu\nu}(x) \frac{\chi_n(y)}{\sqrt{b_0}}$$

## KK Graviton couplings:

$$-\frac{1}{\overline{M}_{Pl}} h^0_{\mu\nu} T^{\mu\nu} - \frac{1}{\widehat{\Lambda}_W} \sum_{n=1}^{\infty} h^n_{\mu\nu} T^{\mu\nu}$$

**where**

$$\widehat{\Lambda}_W \sim \sqrt{2}\,\overline{M}_{Pl}\Omega_0 \sim \text{ TeV},$$

Our choice of parameters:

$$\boxed{\xi \qquad \Lambda_\phi \qquad m_h \qquad m_\phi}$$

Additional parameter for fixing the phenomenology of KK excitations of the gravitons $h^n_{\mu\nu}$,

$$\boxed{m_1 = x_1 \frac{k}{M_{Pl}} \frac{\Lambda_\phi}{\sqrt{6}}}$$

$m_1$ is the mass of the first KK graviton excitation. $x_1 \sim 3.83$ is the first zero of the Bessel function $J_1$.

- Radion-Higgs couplings to gauge bosons and fermions

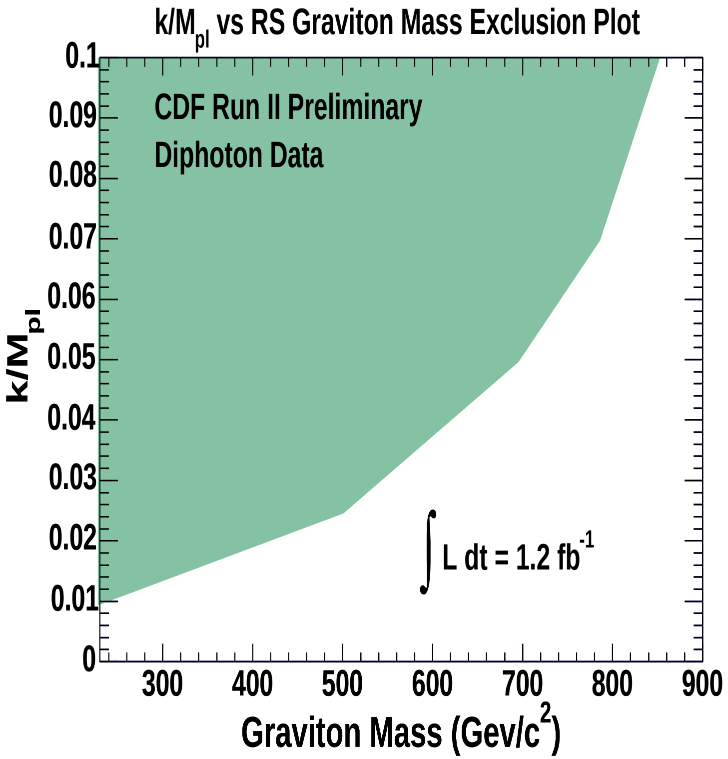
$$\overline{g}_{ZZh} = \frac{g\, m_Z}{c_W}(d + \gamma b)\,, \quad \overline{g}_{ZZ\phi} = \frac{g\, m_Z}{c_W}(c + \gamma a)\,,$$

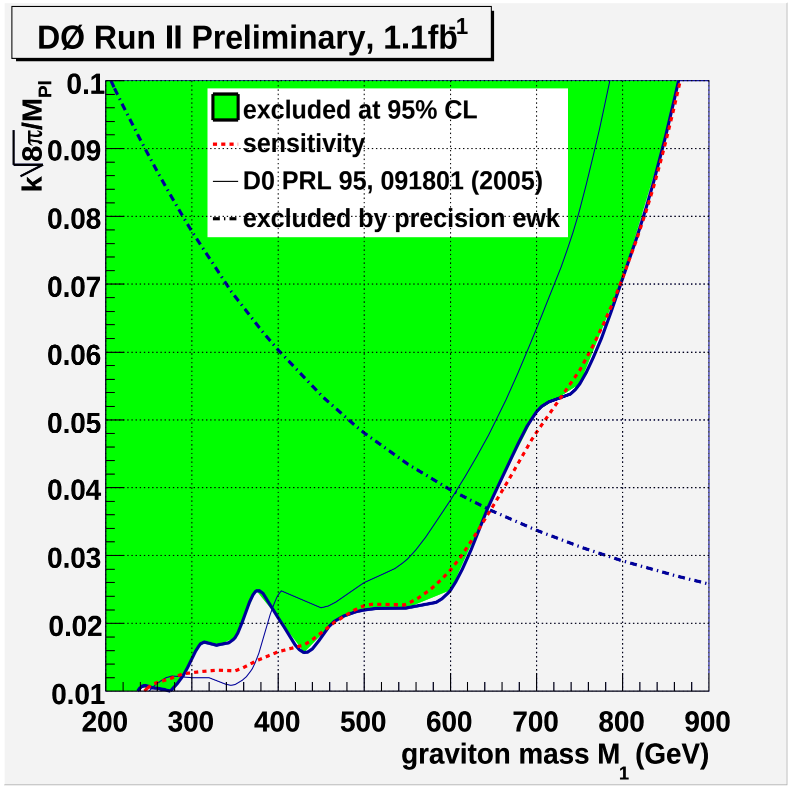
$WW$ couplings: $\frac{g\, m_Z}{c_W} \longrightarrow m_W$

$$\overline{g}_{f\bar{f}h} = -\frac{g\, m_f}{2\, m_W}(d + \gamma b)\,, \quad \overline{g}_{f\bar{f}\phi} = -\frac{g\, m_f}{2\, m_W}(c + \gamma a)\,;$$

$\gamma \equiv v/\Lambda_\phi\,.$

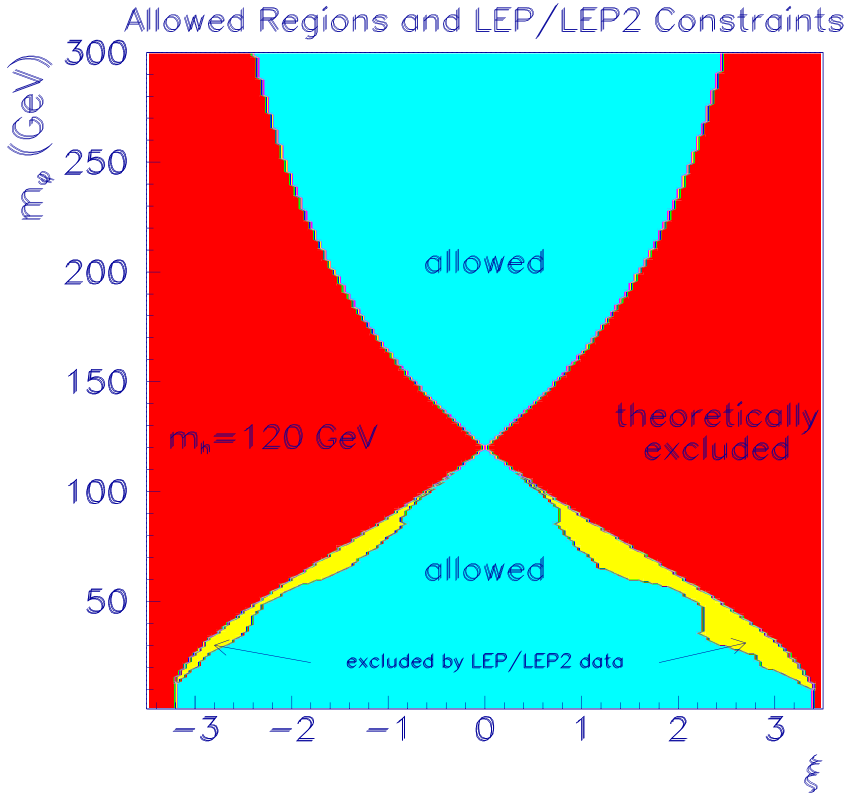
# Run II analysis searches for high mass di-photon states





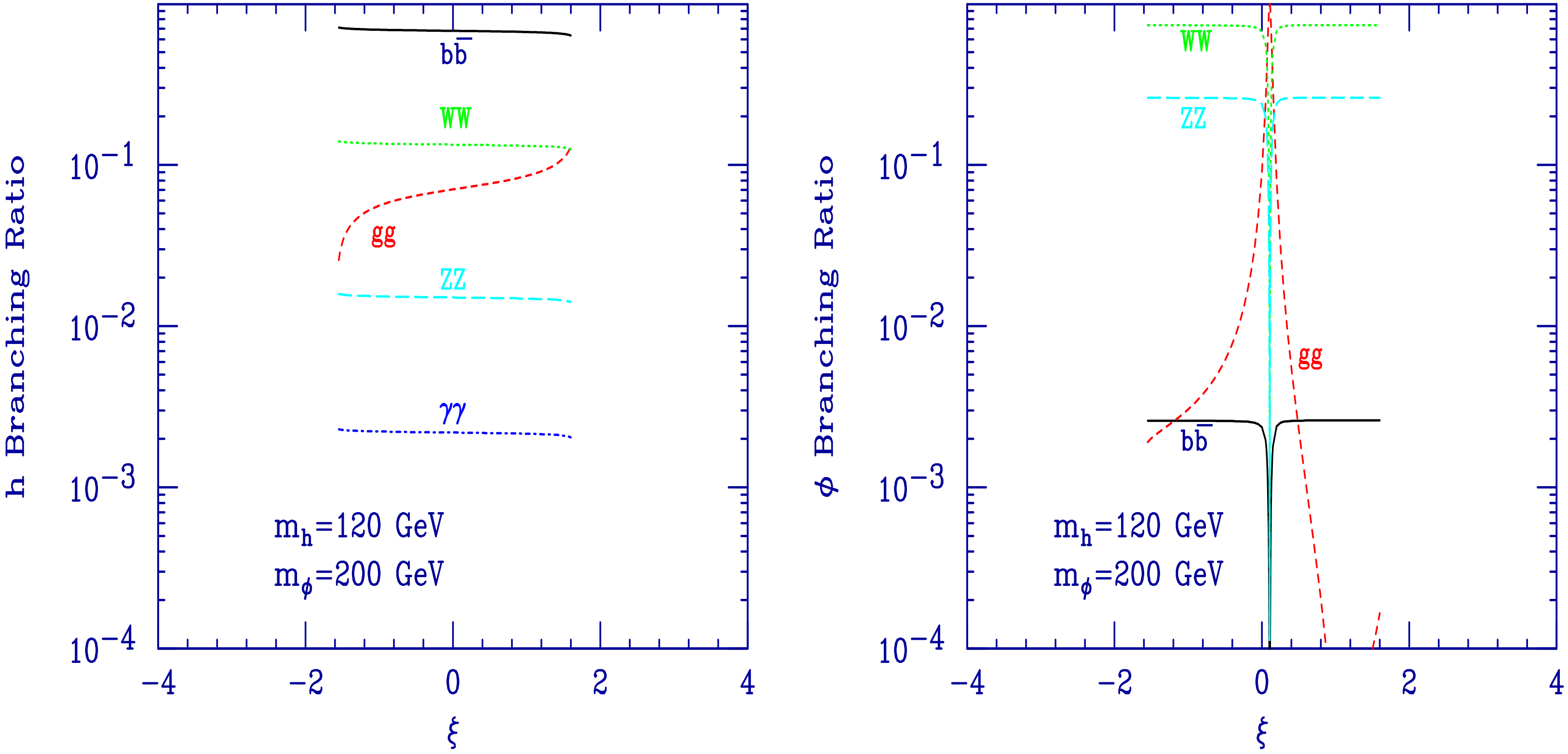
**For example, $k/\overline{M}_{Pl} = 0.1$, $m_1 > 850$ GeV implying $\Lambda_\phi > 5.4$ TeV. Including $e^+e^-$ graviton decay, $m_1 > 889$ GeV (D0 $m_1 > 865$).**

**Allowed regions for $\Lambda_\phi = 5$ TeV and $m_h = 120$ GeV.** The light yellow portion is eliminated by LEP/LEP2 constraints on $g^2_{ZZs}$ (untagged hadronic events) or on $g^2_{ZZs} BR(s \to b\bar{b})$, with $s = h$ or $s = \phi$ (OPAL, LEPHIGGS wg).

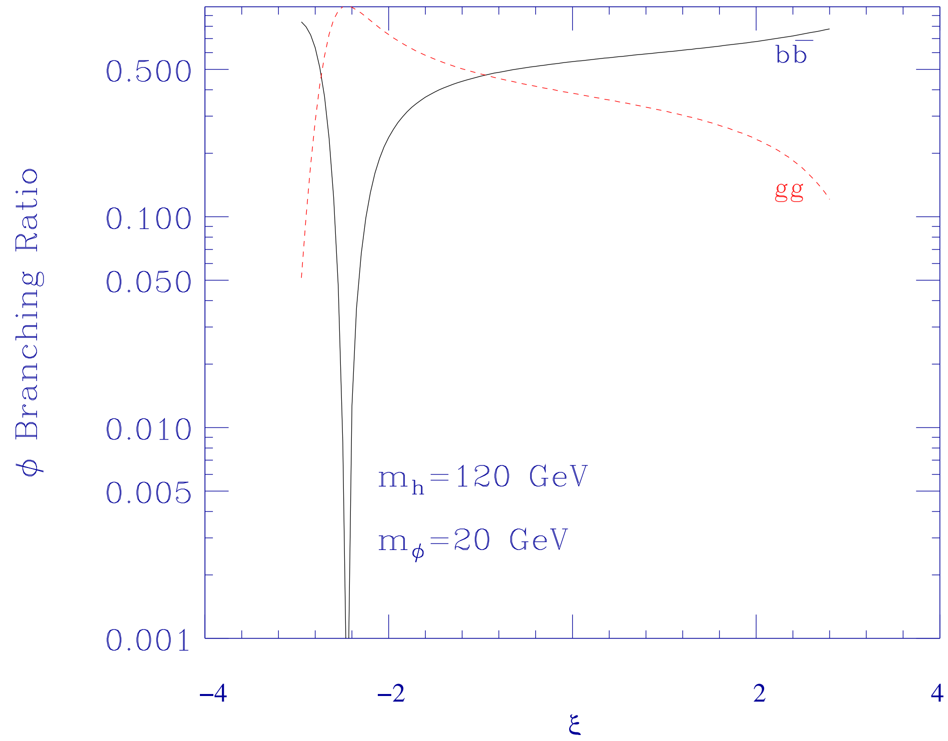


For $m_h = 112$ GeV, almost all excluded. For $\Lambda_\phi = 1$ TeV light radion much more constrained.

# The branching ratios for $h$ (left) and $\phi$ (right) for $m_h = 120$ GeV and $m_\phi = 200$ GeV, $\Lambda_\phi = 5$ TeV.

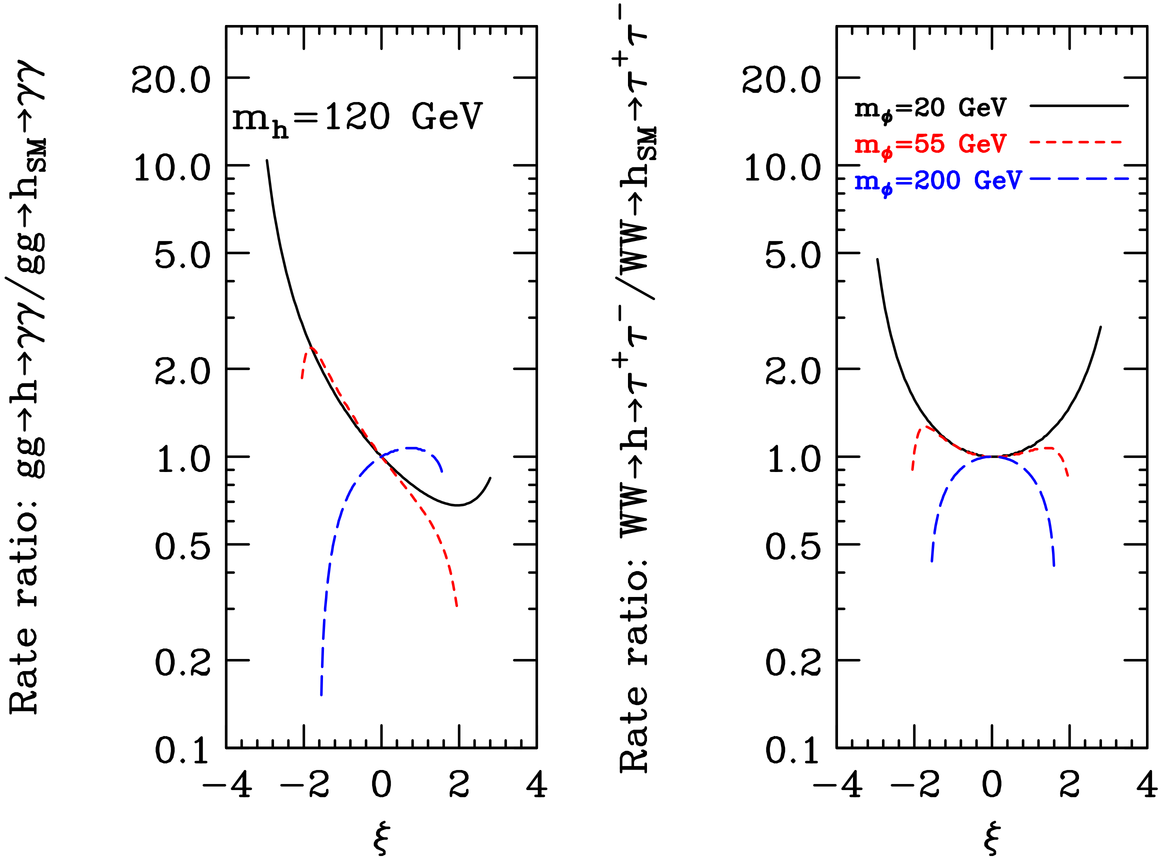


# The branching ratios for $\phi$ decays to $b\bar{b}$, $gg$, for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as functions of $\xi$ for $m_\phi = 20$ GeV

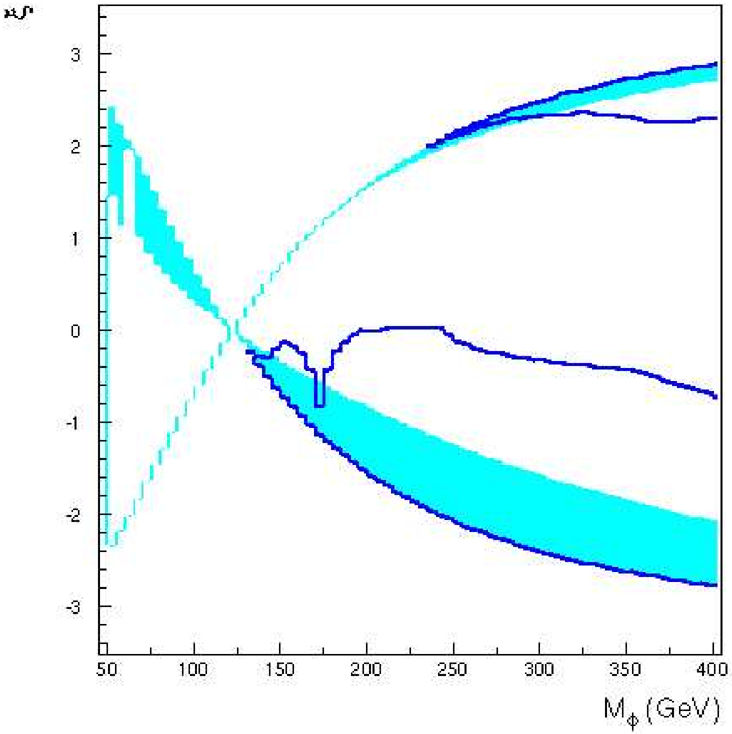


# Prospects for $h$ discovery at LHC

## The ratio of the rates for $gg \to h \to \gamma\gamma$ and $WW \to h \to \tau^+\tau^-$ to the corresponding rates for the SM Higgs boson for $m_h = 120$ GeV and $\Lambda_\phi = 5$ TeV as functions of $\xi$ for $m_\phi = 20, 55$ and $200$ GeV.

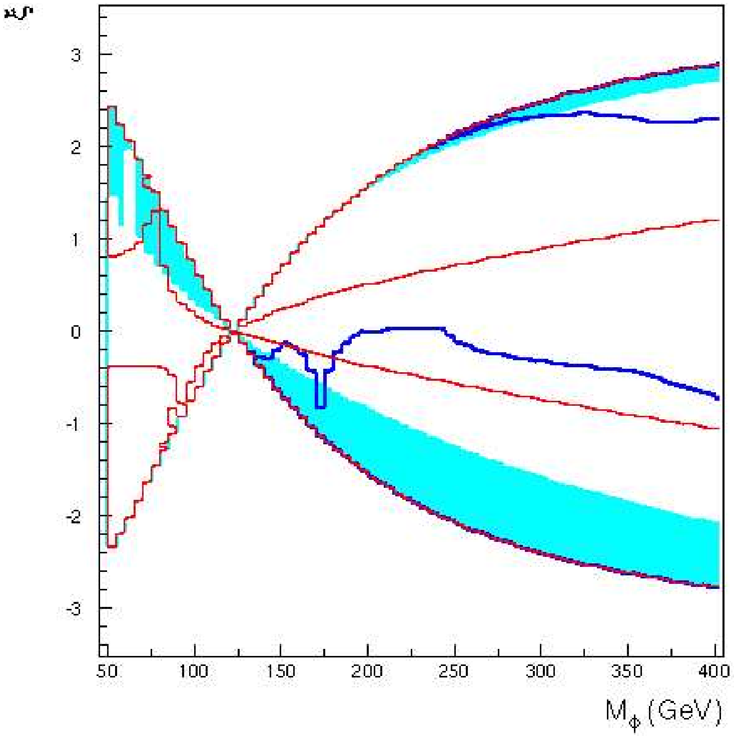


# Complementarity at LHC



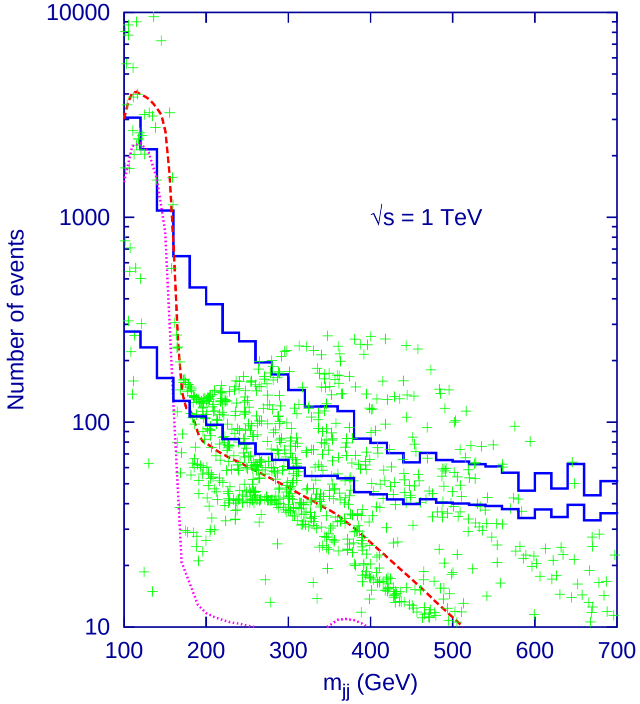
**Regions of $gg \longrightarrow h$ with $h \longrightarrow \gamma\gamma$, $h \longrightarrow ZZ^* \longrightarrow 4\ \ell$, $h\bar{t}t(h \longrightarrow \bar{b}b)$ and $gg \longrightarrow \phi \longrightarrow ZZ^* \longrightarrow 4\ \ell$ detectability at LHC for one expt and 30 fb$^{-1}$. The cyan regions: Higgs signal significance $< 5\ \sigma$. The blue curves: $gg \longrightarrow \phi \longrightarrow ZZ^{(*)} \longrightarrow 4\ \ell$ signal exceeds $5\ \sigma$. For $m_h$=120 GeV and $\Lambda_\phi = $ 5 TeV .**

# Complementarity LHC/ILC



**The red curves: the regions where the ILC measurements of the $h$ couplings to $b\bar{b}$ and $W^+W^-$ would provide a $> 2.5\ \sigma$ evidence for the radion mixing effect. For $m_h$=120 GeV and $\Lambda_\phi =$ 5 TeV .**

# Prospects for $\phi$ discovery at ILC, in $e^+e^- \to \nu\bar{\nu}\phi \to miss + gg$ (Datta, Huitu)

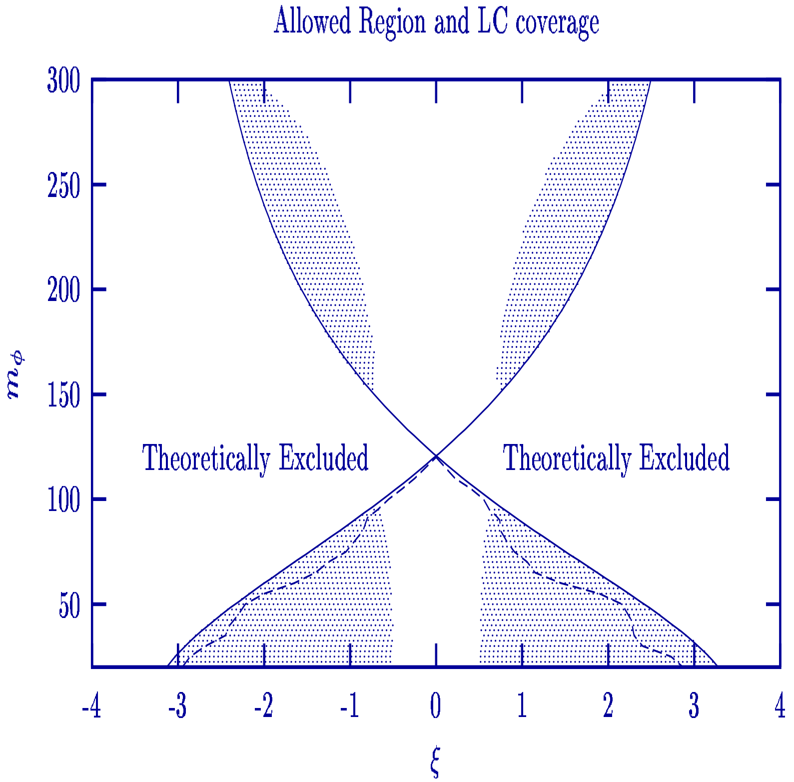


**Number of signal ($+$ for $\xi \neq 0$ and dashed line is for $\xi = 0$), SM Higgs (dotted line) and background (solid histogram) events as a function of the invariant mass of the jets. The upper histogram the actual number of background events. The lower histogram the $5\sigma$ fluctuation of background. Points (representing the signal from Higgs and radion) above the lower histogram can be explored at $5\sigma$. $\Lambda_\phi$= 1 TeV, $m_H$= 150 GeV.**

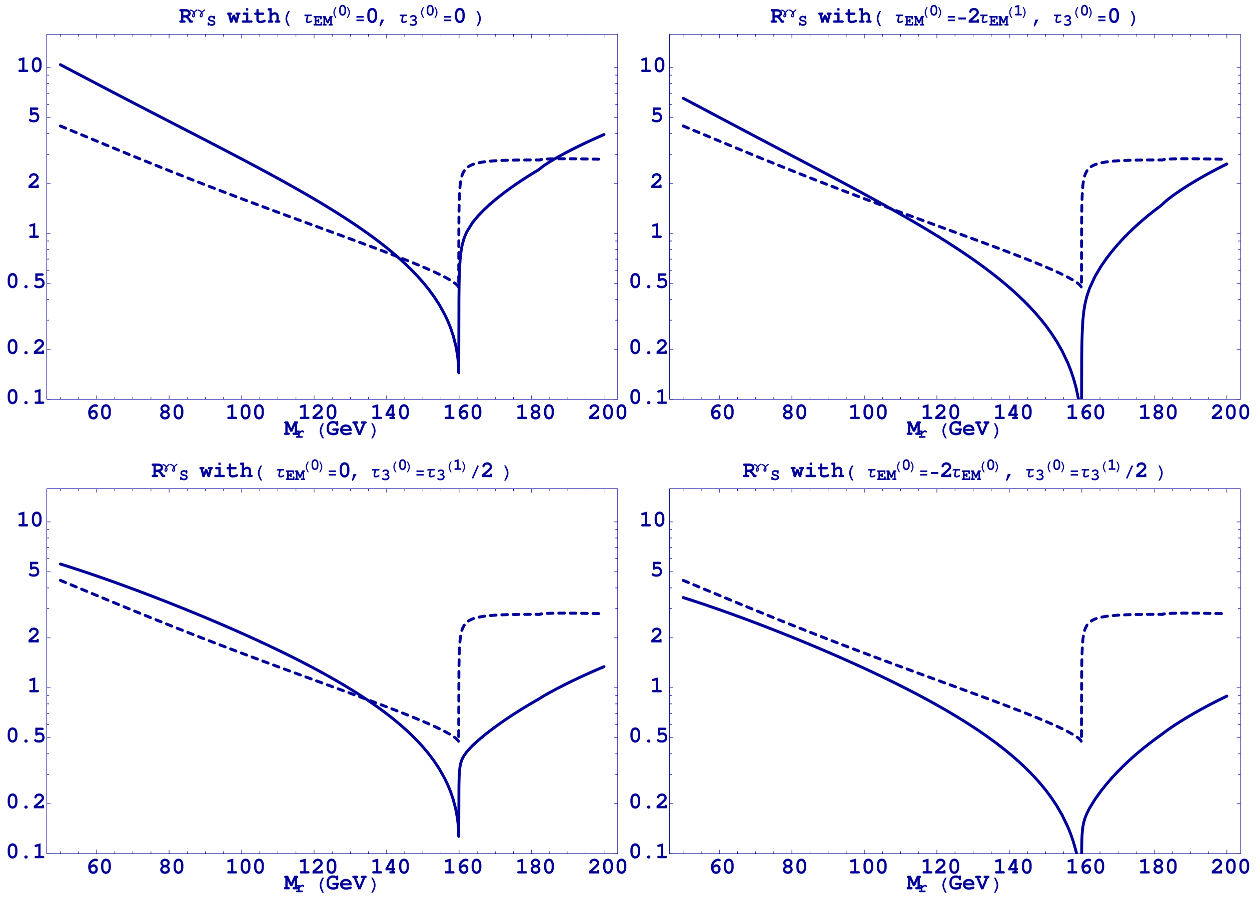
# ILC sensitivity to the graviton-Higgs-radion coupling

(Cheung, Kim, Song)

**The dotted regions are for $\sigma_{tot}(e^+e^- \to h^n_{\mu\nu} \to h\phi \to b\bar{b}b\bar{b}) > 0.03$ fb. $m_h$= 120 GeV, $\Lambda_\phi = 5$ TeV.**



# Radion phenomenology in RS model with bulk fermions and gauge bosons (Csáki, Hubisz, Lee)

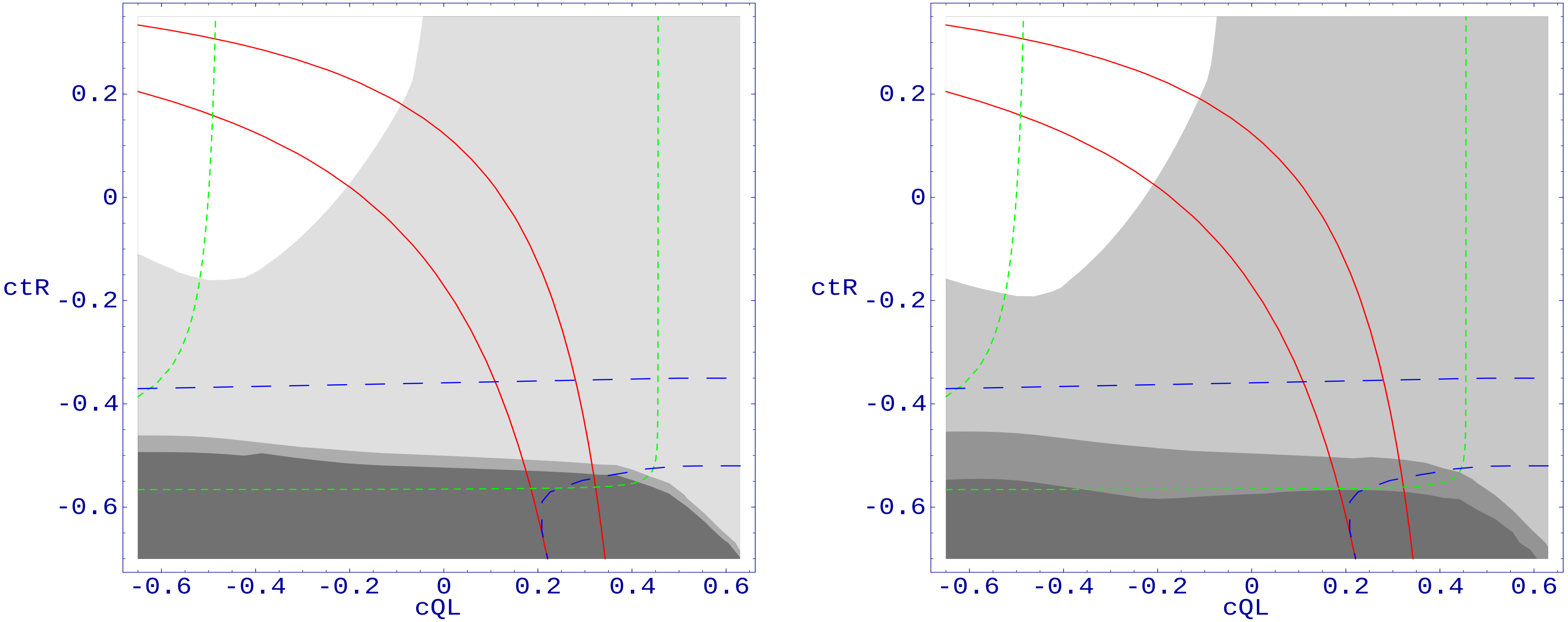


**Ratio $R_S^{\gamma\gamma} = S(\phi)/S(h_{SM})$ with $\Lambda_\phi = 2$ TeV for various combinations of brane kinetic terms for the photon and the gluon. Dashed is RS model.**

**In some region more likely to find a radion!**

# Higgs phenomenology in RS model with bulk fermions and gauge bosons (Djouadi, Moreau)

## Effect of new quark $b'$ the $SU(2)_R$ partner of the heavy top quark doublet in $gg \longrightarrow H$



**Ratio $\mathcal{R} = \sigma_H^{RS}/\sigma_H^{SM}$ for fixed value $c_b = 0.6$. The filled regions correspond from white to darkest grey to, respectively, the intervals $\mathcal{R} \in [1, 0.75]$, $[0.75, 0.25]$, $[0.25, 0.1]$ and $\mathcal{R} \leq 0.1$ (left), $\mathcal{R} \in [1, 1.2]$, $[1.2, 2]$, $[2, 4]$ and $\mathcal{R} > 4$ (right).**

# Conclusions

**Higgs phenomenology can be modified in extra dimension models**

## ADD

- For a light Higgs boson the process $pp \to W^*W^* + X \to Higgs, graviscalars + X \to invisible + X$ will be observable at the $5\ \sigma$ level at the LHC for a large portion of the Higgs-graviscalar mixing ($\xi$) and $D$-dimensional Planck mass ($M_D$) parameter space where channels relying on visible Higgs decays fail to achieve a $5\ \sigma$ signal.
- However LHC will not be able to determine $M_D$, $\xi$ and $\delta$
- Measurements of $\Delta BR(H)/BR(H)$ for the visible and the invisible channels and $\gamma + \not{E}_T$ at the $e^+e^-$ ILC combined with LHC determine with good accuracy $M_D$, $\xi$ and $\delta$ as long as not both $\delta$ and $M_D$ are large.

# RS

- LHC detection of the $h$ in $gg \to h \to \gamma\gamma$ not guaranteed. LHC detection of the $\phi$ in $gg \to \phi \to \gamma\gamma$ likely to be difficult unless $\Lambda_\phi \sim$ 1-2 TeV and gauge bosons in the bulk.
- However, for almost the entire region of the parameter space where the Higgs signal significance at LHC $\leq$ 5 $\sigma$, the $gg \to \phi \to Z^0 Z^{0(*)} \to 4\ \ell$ process can be observed.
- A $e^+e^-$ linear collider would complement the LHC both for the Higgs observability and for the detection of the radion mixing effects, through the precision measurements of the individual Higgs particle couplings.
- Other interesting channels for LHC/ILC:

$pp, e^+e^- \to h^n_{\mu\nu} \to h\phi$

$e^+e^- \to \nu\bar{\nu}\phi \to miss + gg$

$\phi \to hh \to bb\gamma\gamma, 4b's, bb\tau\tau$; for $m_\phi = 300$ GeV, LHC sensitive to $\Lambda_\phi \leq 3$ TeV.

- If at LHC an intermediate mass scalar observed its non SM-like nature can in some cases be detected through measurements of rates.
- One particularly interesting complication for $\xi \neq 0$ is the presence of the non-standard decay channel $h \to \phi\phi \to bbgg, 4b's$.